NANOTRANSISTORS FROM METAL AND METALLOID COMPOUND NANOTUBES

Bagavathi Chandrasekara

Abstract— The escalating trend of chip integration and miniaturization has dared the designers to seek to a nascent phenomenon to save the Moore's law. Due to continuous reduction in device size, the so-far-unseen quantum effects have dominated the device physics. The solution to this crisis is nanoelectronics. Nano structures are used to develop new devices by utilizing the quantum effects. III group compounds have been known for their special properties as semiconductors in electronics. By including nanoscale nature with III group compounds, greater advantages can be obtained. III group nitride nanotubes have been investigated in many works. The nanotubes under discussion are boron nitride nanotubes and gallium nitride nanotubes. The phenomenon used for analysis in this work is Density Functional Theory (DFT). The characteristics of a device can be deduced from the electronic cloud structure around the device through density functional theory. In this work, III group nitride nanotubes are employed as transistor channels and their characteristics are scrutinized through simulation studies.

Index Terms— Gallium nitride nanotube, Nanotube transistor, Third group nanotubes, Density Functional Theory, Simulation of nanomaterials

1 INTRODUCTION

Nanotechnology refers to integration of manmade materials of infinitesimal sizes into large components of devices and structures. Nano structures have made life comfortable in a variety of ways through faster, smaller and safer devices. Nano particles have made so-far-impossible circumstances to a possible scenario through simple processes and configurations.The miniaturization has provided an inherent obstacle of facing with the intricate quantum consequences.Nanotechnology is presently in a quasi state of development in the process of becoming an indispensable phenomenon in almost all engineering and scientific fields. It has become the hottest focus of research and analysis worldwide. Scientists are searching for new applications so that the cost encountered for the synthesis of nanomaterials is justified. Recently developed chips named Ivy Bridge by Intel Corporation have reached 22 nm device size by using tri-gate design of 3D transistor technology [1]. Intel Corporation is expecting 14 nm technology in 2014.

According to International Technology Roadmap for Semiconductors (ITRS), the promising materials after silicon technology would be III-V semiconductors, nanowires and carbon nanotubes [2]. III group nitride nanotubes have been investigated in many works [3], [4], [5] and [6]. 4D transistors have designed by stacking the channels in the vertical direction [7]. This new-type of transistors were fabricated recently by replacing silicon with Indium Gallium Arsenide. Boron is a metal and Aluminum, Gallium and Indium are metalloids. The nanotubes under discussion are boron nitride nanotubes [8], [9] and gallium nitride nanotubes [10]. Boron nitride nanotubes are the first compound nanotubes to be synthesized after carbon nanotubes. Gallium nitride nanotubes had been synthesized as single crystals and they have exhibited excellent electrical and optical characteristics. The phenomenon used for analysis in this work is Density Functional Theory (DFT) [11]. Density functional theory is a quantum mechanical modeling method used in physics and chemistry to investigate the electronic structure of many-body systems, in particular atoms, molecules [12], and the condensed phases. DFT is mostly suited for analysis in nano-scale systems.

In electronics, transistors are the basic ingredient in the development of new technology devices. Nanotransistors are transistors synthesized using nanostructure channels with source and drain. The nanostructures used in the transistors can be nanotubes [13], nanowires [14] and graphene [15]. Transistors are resistors controlled by a third terminal called gate. The electron flow in the semiconducting channel between heavily-doped source and drain regions are controlled by voltage applied on the third electrode. According to Moore's law, the size reduction reduces the channel length and the transistor faces various short channel effects and leakage dissipation. To deal with this leakage problem, semiconducting channels are replaced by nanostructures with semiconducting property.

The main motivation of this work is that III-V compound semiconductors are used for high speed device applications. They are essential elements of the highest-performance optical sources and detectors, and are being used increasingly in high-speed and high-frequency digital and analog devices. Using III-V compound nanotubes, it would be more advantageous to design nano transistors.

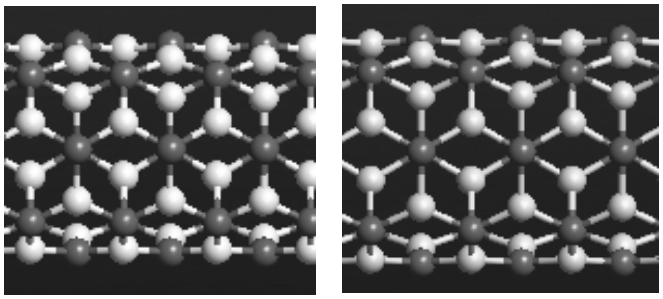
2 THEORETICAL CONCEPTS

2.1 Thid group nitrides

Boron-Nitride (BN) was the first chemical compound to replace elemental Carbon in nanotubes because of its hexagonal structure which is similar to graphite [9]. Boron Nitride nanotubes were first synthesized in 1995 [2]. Substitution of the Carbon-Carbon pairs wholly by the Boron–Nitrogen pairs in

Bagavathi Chandrasekara is currently working as a Assistant Professor in the Department of Electronics and Communication Engineering of K.S.R. College of Engineering, Tiruchengode – 637 215.
E-mail: bagavathi03amrita@gmail.com

the hexagonal arrangement of graphite leads to the formation of a wide array of two-dimensional segments. BN crystallizes in a graphite-like structure and can simply be viewed as replacing a Carbon–Carbon pair in the Graphene sheet with the iso-electronic Boron-Nitrogen pair. Aluminum nitride (AlN) nanotubes have been found to have semiconducting band gaps of 2.84 to 3.95 eV. The lower strain energy is required in order to wrap up an AlN graphitic sheet into a tube. Contrary to the cases of carbon nanotubes, the band gap of AlN nanotubes rises with the growing diameter of the tubes and inundates at a value consequent to the calculated band gap of an AlN hexagonal sheet [16]. Gallium nitride (GaN) nanotubes were synthesized in 2005 [10]. They have been identified with excellent electronic and optical properties.



(a) (b)

Fig 1 (a) Boron Nitride nanotube (b) Aluminum nitride nanotube

2.2 Nanotube Transistors

Nanotransistors are generic model of a nano device in electronics. The nanotransistor consists of a nanotube as a channel for charge carriers and two contacts on either ends of the nanotubes to provide a continuous stream of electron transfer. The third contact is the gate terminal which controls the flow of electrons between the contacts. The contacts are generally termed as source and drain derived from a MOSFET structure. The first Carbon nanotube field effect transistor (CNTFET) was developed in 1998 [13]. Carbon nanotube modeling is essential for Group III-V nanotube transistor modeling because of similar characteristics among carbon and compound semiconductors. The Strain energies and lattice structure of these compound semiconductors are similar to that of carbon. Carbon nanotube FET was worked in a similar way as that of conventional MOSFET but for their potential barriers of the nanotube with the contacts. Previously, metals were used as contacts instead of doped nanotube due to the difficulty of selectively doping a nanotube.

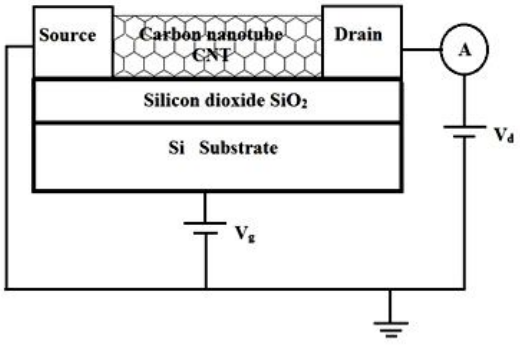


Fig 2 Carbon nanotube transistor

Nanotube channels tend to form Schottky barrier with most of the contact metals as their work function mismatch with the electron affinity of the nanotube.Recently fabrication techniques have developed to dope the nanotubes heavily so that they can form contacts [18].

In a previous work, Gallium nitride nanotube transistor [19] has been designed by using the density functional theory and quantum transport in nano regime [21]. The design was proposed with design parameters such as temperature, Fermi level, density of states, lattice constant, bond length, electrochemical potential of contacts, etc. Certain discrepancies have been reported in the transition region of the IV characteristics of the nanotube transistor attributed to the improper coupling of the contacts with the nanotube channel. The current curve of the transistor can be approximated by a tenth degree polynomial with a correction of 0.78%.

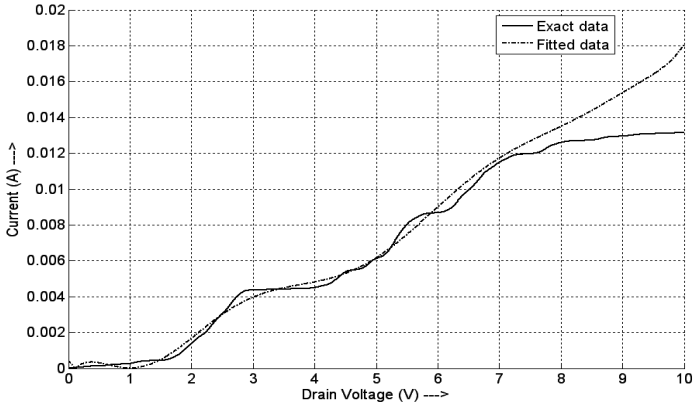


Fig 3 Fitting of polynomial curve with Current-Voltage characteristics of GaN nanotube transistor [19]

Nanotransistors discussed in this work utilize Aluminum nitride nanotube and boron nitride nanotube as transistor channels. The bond length of aluminum nitride nanotube and boron nitride nanotube is 1.6 Å and 1.4 Å respectively. Density of states of the nanotubes is the input to the device model that relates to the conducting character of the device.

$$I = \frac{q}{\hbar}\int_{-\infty}^{\infty} dE D_{\varepsilon}(E)\frac{\gamma_1\gamma_2}{\gamma_1+\gamma_2}[f_1(E)-f_2(E)] \quad (1)$$

The current equation (1) derived from [21] is used in the design to calculate current due to the density of states, escape rates and Fermi level of the device.

2.3 Density Funcitonal Theory

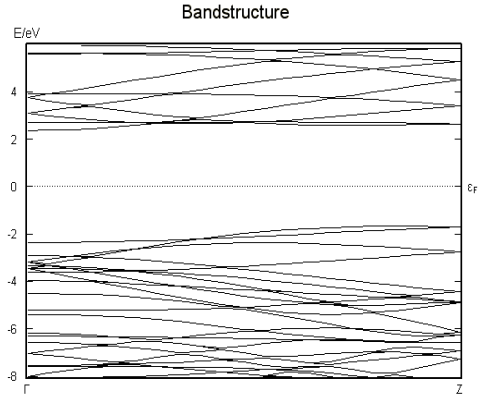
Density functional theory (DFT) is a wave mechanics-based modeling method especially tailored to be used in the investigation of electronic structure of many-body systems [22]. The main entities of density functional theory are electron density and concepts that govern the inferences obtained from the functional that are derived from electron density. DFT is among the most popular and versatile methods available in condensed-matter physics, computational physics, and computational chemistry. Density functional theory determines

characteristics of a device based on the distribution of electron around the device.

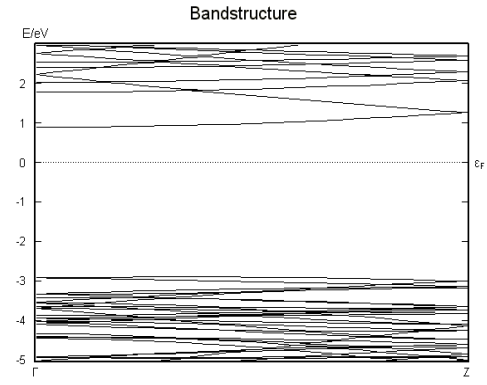
The characteristics such as total energy can be determined from electron density n(r). When the number of electrons in the device increases, the interaction among the electrons has to be taken into account for accurate calculations. To account for such interactions, local density approximation [23] is used so that the electron density in a small area is integrated to approximate the electron-electron interaction of the entire device.

3 SIMULATION RESULTS

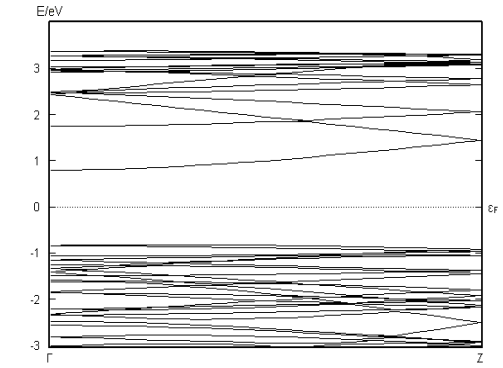
This work was to illustrate the possibility of nanotransistors using compound semiconductor nanotubes and discuss their properties and characteristics.



(a)



(b)



(c)

Fig 4 Bandstruture of nanotubes (a) BN nanotube (4, 4) (b) AlN nanotube (4, 4) (c) GaN nanotube (4, 4)

Comparison of BN, AlN and GaN nanotubes show that they have similar density of states and band structure. From the band structure of the nanotubes as shown in fig.3, it can be ensured that all of the nanotubes are semiconducting. The nanotubes are different based on their molecular configuration as Boron, aluminum and gallium has different atomic radii.

Transistor model follows the model of Gallium nitride nanotube transistor designed in simulation using MATLAB and Atomistix tool kit [17], [20].

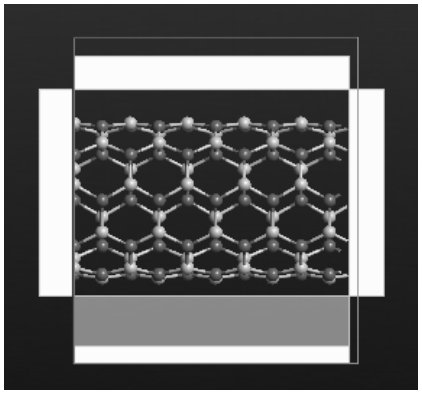
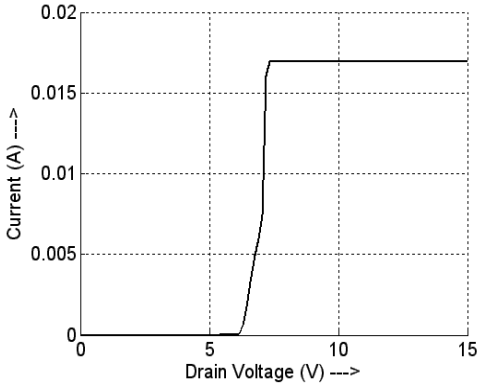
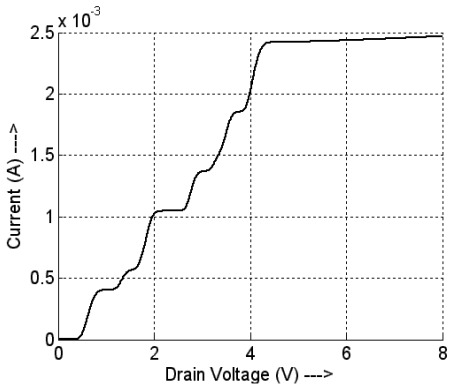


Fig 5 Transistor simulation in Atomistix Toolkit

In this current work, the model is extended for BN and AlN nanotube transistors. The parameters used are same as that used in Gallium nitride nanotube transistor except for those which depend on the chemical composition of the transistor. The bond length, source Fermi level and density of states are different.



(a)



(b)

Fig 6 (a) Aluminum nitride nanotube transistor (b) Boron nitride nanotube transistor

The result shows that the transistor model is suited well for Aluminum nitride nanotubes but the threshold voltage is quite high compared to that of boron nitride nanotube and gallium nitride nanotube transistor. The curve has a steep and smooth rise in the transition region in aluminum nitride nanotube transistors.

4 CONCLUSION

Modern trends indicate that silicon can no longer the electronics industry as its limits has been reached. Recent invention of 4D transistors has accelerated the research of the III-V compound semiconductors. In this work, it has been proved that BN, AlN and GaN nanotubes can act as nanotransistor channels with suitable modifications in the composition of channels. The incoherence in the characteristic of BN nanotube transistor can be reduced by using appropriate contact materials of atomic characteristics similar to that of BN nanotubes.

ACKNOWLEDGMENT

The author wishes to thank Almighty for knowledge. She wishes to thank her guide Dr. K. A. Narayanankutty for guiding through her research work in master's degree. Last but not the least; she is indebted to her parents N. Chandrasekara, R. Santhakumari, Brother C. Senthil Kumaran and husband K. V. Shivakumar for their moral support and strength.

REFERENCES

[1] J. Kavalieros, B. S. Doyle, S. Datta, G. Dewey and R. Chau "Tri-Gate Transistor Architecture with High-k Gate Dielectrics, Metal Gates and Strain Engineering," Digest of Technical Papers VLSI Technology Symposium, pp.62-63, June 2006

[2] ITRS: International technology roadmap for semiconductors: Process integration, devices, and structures, Technical report, www.itrs.net, 2009.

[3] ZheChuanFeng, "III-Nitride Devices and Nanoengineering", Imperial College Press, ISBN-13 978-1-84816-223-5, 2008.

[4] Min Zhang, Zhong Min Su, Li Kai Yan, Yong Qing Qiu, GuaHua Chen, Rong Shun Wang, "Theoretical interpretation of different nanotube morphologies among Group III (B, Al, Ga) Nitrides," Chemical Physics Letters, Vol. 408, pp 145 – 149, 2005.

[5] Yeau Ren Jeng, Ping Chi Tsai and TeHua Fang, "Tensile Deformation of Tubular Structures of Nitride-based Nanotubes: Brittle and Weak Behavior", Tamkang Journal of Science and Engineering, Vol. 8, pp 191 – 195, 2005.

[6] Engin Durgun, SalimCiraci, "A Theoretical study on silicon and III-V compound nanotubes" Journal of Turk Physics, Vol. 29, pp. 307 – 318, 2005.

[7] X.W. Wang, J. Shao, A.T. Neal, M.J. Manfra, R.G. Gordan, P.D. Ye, "III-V 4D transistors", 70th Annual Device Research Conference (DRC), June 2012.

[8] X. Blase, A. Rubio, S. G. Louie and M. L. Cohen, "Stability and Band Gap Constancy of Boron Nitride Nanotubes", Europhysics Letters, Vol. 28, pp. 335-340, 1994.

[9] N. G. Chopra, R. J. Luyken, K. Cherrey, V. H. Gespi, M. L. Cohen, S. G. Loute, A. Zettl, "Boron Nitride nanotubes," Science, Vol. 269, pp 966 – 969, 1995.

[10] Joshua Goldberger, Rongrui He, Yanfeng Zhang, Sangkwon lee, Haoquan Yan, Heon Jin Choi, Peidong Yang, "Single Crystal Gallium Nitride nanotubes", Nature, Vol. 422, pp 599 – 602, 2003.

[11] W. Kohn, A. D. Becke, and R. G. Parr, "Density Functional Theory of Electronic Structure," Journal of Physical Chemistry, Vol.100, pp 12974-12980, 1996.

[12] Robert C. Parr, Weitao Yang, "Density-Functional Theory of the Electronic Structure of Molecules", Annual Review of Physical Chemistry, Vol. 46, pp 701-728, 1995.

[13] S. J. Tans, R. M Verschueren, and C. Dekker, "Room temperature transistor based on a single carbon nanotube", Nature, Vol. 393, pp 49 – 52, 1998.

[14] Ho-Young Cha, Huaqiang Wu, MvsChandrashekhar, Y C Choi, S Chae, G Koley and M G Spencer, "Fabrication and characterization of pre-aligned gallium nitride nanowire field-effect transistors", Nanotechnology, Vol. 17, pp 1264-1271, 2006.

[15] PiaJuliane Wessely, Frank Wessely, Emrah Birinci, Udo Schwalke, and Bernadette Riedinger, "Transfer-free fabrication of graphene transistors", Journal of Vacuum Science and Technology B, Vol. 30, 03D114, 2012.

[16] Mingwen Zhao, Yueyuan Xia, Dongju Zhang, and Liangmo Mei, "Stability and electronic structure of AlN nanotubes", Physical Review B, Vol. 68, pp 235415, 2003.

[17] AtomistixToolKit version 12.8.0, QuantumWise A/S (www.quantumwise.com)

[18] KhairulAlam, Roger lake, "Role of Doping in Carbon Nanotube Transistors with Source/Drain Underlaps", IEEE transactions on Nanotechnology, Vol. 6, No. 6, November 2007.

[19] Bagavathi Chandrasekara, K A Narayanankutty, "Gallium Nitride Nanotube and its Application as Transistors" in International Journal of Computer and Applications (IJCA), ISSN 0975-888, Vol. 47, No. 14, pp 39 – 44, June 2012.

[20] M. Brandbyge, J.-L. Mozos, P. Ordejón, J. Taylor, and K. Stokbro, "Density Functional method for non-equilibrium electron transport", Physical Review B, Vol.65, pp. 165401, 2002.

[21] Supriyo Datta, "Quantum Transport: From atom to transistor," Cambridge University Press, 2005.

[22] R.G. Parr and W. Yang, "Density-Functional Theory of Atoms and Molecules," Oxford, 1989.

[23] J.P. Perdew, Alex Zunger, "Self-interaction correction to density-functional approximations for many-electron systems," Physical Review B, Vol. 23, pp. 5048-5079, 1981.